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PRIMARY SCHOOL TEACHERS' PCK DEVELOPMENT FOR MODELING-BASED INSTRUCTION: A KNOWLEDGE EXCHANGE PERSPECTIVE WITHIN A PROFESSIONAL LEARNING COMMUNITY

Hyunju Kim,
Kiyoung Lee

Abstract. *Supporting primary school teachers' Pedagogical Content Knowledge (PCK) development for modeling-based instruction (MBI) remains a key challenge in science teacher education. Professional Learning Communities (PLCs) offer a promising context for this professional growth. This study examined the PCK development processes of three primary school teachers with varying experience levels as they participated in five MBI-focused PLC sessions. PCK changes were traced using an integrated analytical framework that combined the Interconnected Model of Teacher Professional Growth (IMTPG) with the Refined Consensus Model (RCM). Findings revealed positive growth across PCK components, though pathways varied. While curriculum knowledge development was often characterized by refinement based on prior knowledge (change sequences), growth in knowledge of student understanding, instructional strategies, and assessment typically demonstrated more complex, interconnected growth networks involving dynamic knowledge exchange, shaped by interactions among personal, collective, and enacted PCK, as well as individual orientations. The study highlights the potential of PLCs as spaces for practice-based learning, supporting sustained PCK development, and demonstrates the utility of the combined IMTPG–RCM framework for analyzing the nuances of teacher growth over time.*

Keywords: *modeling-based instruction, pedagogical content knowledge, professional learning communities, qualitative case study, science education*

Hyunju Kim
Seoul Aju Elementary School, South Korea
Kiyoung Lee
Kangwon National University, South Korea

Introduction

Effective science teaching is highly dependent on a specialized form of teacher knowledge that enables students to understand scientific concepts and engage in scientific practices. This knowledge, conceptualized as Pedagogical Content Knowledge (PCK) (Shulman, 1987), serves as a core component of teacher expertise, distinguishing it from general pedagogical and content knowledge, and directly influences the quality of teaching and students' academic achievement (Baumert et al., 2010).

Recognizing and understanding teachers' PCK is widely considered essential to improving the quality of science education (Kind, 2009; van Driel & Abell, 2010), and accordingly, numerous studies have been conducted to deepen insights into how PCK is developed and applied (National Research Council, 1996). However, as PCK has been increasingly applied in science education research, differing interpretations of its structure and evolution have emerged, creating challenges for empirical inquiry and policy development (Settlage, 2013). To address this, science education researchers proposed the Refined Consensus Model (RCM) of PCK, developed through two major summits held in 2012 and 2015 (Carlson et al., 2019).

The RCM conceptualizes PCK as comprising three realms: collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK). This model posits that teachers' professional growth occurs through knowledge exchanges across these realms. In particular, the RCM framework shows that the development of teacher expertise is a dynamic process of continual reconstruction, rather than a static accumulation of knowledge. This occurs as teachers engage in planning ($ePCK_P$), teaching ($ePCK_T$), and reflecting ($ePCK_R$), during which their pPCK is transformed into ePCK, reshaped through reflection, feeding back into their evolving pPCK.

In this context, Professional Learning Communities (PLCs) have gained prominence as a practical approach to promoting the development of teach-

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ers' PCK. PLCs are recognized as an effective environment for enhancing teacher expertise through collaborative learning and peer reflection (Vescio et al., 2008). They offer a space for teachers to refine and adapt teaching strategies to suit their classrooms better, thereby fostering the growth of PCK.

Meanwhile, science education has increasingly emphasized model-based instruction (MBI). This approach encourages students to engage in epistemic practices like scientists—constructing, representing, and refining their understanding of scientific concepts through models (Justi & Gilbert, 2002; NGSS Lead States, 2013). However, implementing MBI presents new challenges for teachers, as it requires professional knowledge of teaching strategies and a deep understanding of student learning and assessment. Therefore, the quality of MBI primarily depends on teachers' PCK (Nelson & Davis, 2012). Despite its potential, scientific modeling remains a relatively unfamiliar and challenging teaching method for many teachers (Justi & Gilbert, 2002), and its classroom adoption has been limited (Suk & Yoon, 2022). A commonly cited reason is teachers' limited understanding of MBI (Crawford & Cullin, 2004; Louca & Zacharia, 2012; Oh & Oh, 2011; van Driel & Verloop, 2002; Vo et al., 2019). Teachers' ability to design practical lessons based on modeling knowledge and to provide meaningful support for students' modeling activities is essential for MBI's success (Louca & Zacharia, 2012). Thus, understanding and supporting the development of teachers' PCK is critical for the practical enactment of MBI.

Theoretical Background

Toward a Refined Understanding of PCK: The Role of the RCM

PCK, first proposed by Shulman (1986, 1987), refers to the unique professional knowledge teachers employ to deliver specific content to specific students effectively. Since its introduction, PCK has become a central concept for understanding teacher expertise in science education. Numerous studies have attempted to define its components, structure, and characteristics. However, these efforts have also led to a proliferation of diverse interpretations, resulting in variations in how PCK is understood among scholars (Settlage, 2013). Key areas of debate include whether PCK constitutes a form of knowledge, skill, or disposition; whether it is topic-specific or general; and whether it is individual or collectively held within a community (Chan & Hume, 2019; Fernandez-Balboa & Stiehl, 1995; Hashweh, 2005; Smith & Banilower, 2015; van Driel et al., 1998).

To reconcile these differences and advance a more refined understanding of PCK, many researchers have attempted to elucidate its components (Abell, 2007; Gess-Newsome, 1999; Grossman, 1990; Magnusson et al., 1999; Park & Chen, 2012; Park & Oliver, 2008a, 2008b; Rosenkranzer et al., 2017; Roth et al., 2011). Among these models, the framework proposed by Magnusson et al. (1999) remains one of the most widely used. This model identifies five key components of PCK: orientation toward teaching science, knowledge of the curriculum, knowledge of students' understanding, knowledge of instructional strategies, and knowledge of assessments. This approach provided a valuable foundation for analyzing the substance of teachers' knowledge (Chan & Hume, 2019).

However, the scholarly conversation progressed beyond merely identifying these static components to examining how PCK develops and is enacted in teaching practice. As part of this progression, two international summits were convened, leading to the creation of a Consensus Model (CM) and, subsequently, a Refined Consensus Model (RCM) (Carlson et al., 2019; Gess-Newsome, 2015). While the initial CM provided a shared language, it was critiqued for its limited capacity to explain how teachers dynamically enact PCK in real classroom settings (Carlson et al., 2019).

Carlson et al. (2019) introduced the RCM to address these limitations, offering a structured framework for interpreting the various dimensions of PCK. The RCM categorizes PCK into three distinct realms: collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK), and conceptualizes these realms as interacting through dynamic processes of knowledge exchange. cPCK represents canonical knowledge constructed and shared within research and teaching communities; pPCK encompasses the individual teacher's accumulated knowledge and teaching orientations derived from experience; and ePCK represents the knowledge mobilized during planning ($ePCK_P$), teaching ($ePCK_T$), and reflection ($ePCK_R$) within actual teaching contexts. The RCM thus frames PCK not as a static list of components but as a dynamic entity that is constantly reconstructed through practice.

The RCM's emphasis on knowledge exchange is particularly valuable for this study. It provides an analytical lens to move beyond simply identifying what teachers know. Instead, it illuminates how that knowledge is shared, challenged, and transformed within a collaborative professional community. Therefore, the RCM offers an ideal framework for analyzing how primary school teachers, when grappling with the complexities of a new pedagogy like MBI, negotiate and build their PCK through interactions with their peers.

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Professional Learning Communities as a Context for PCK Development

Professional Learning Communities (PLCs) have been widely recognized as an effective environment for enhancing teacher expertise through collaborative learning and reflective dialogue (Vescio et al., 2008). According to Louis et al. (1995), the successful operation of PLCs depends on key community elements such as shared norms and values and, crucially, reflective dialogue. This structured, reflective dialogue environment provides the fertile ground for the knowledge exchange central to PCK development. As Carlson et al. (2019) also suggested, PLCs offer a productive context for facilitating the knowledge exchange within the realms of PCK.

This study's PLC was structured using protocols to ensure these collaborative discussions were focused and productive. Protocols are procedural tools that facilitate structured communication, fostering deeper conversations and inquiries within the community (Galloway, 2004; McDonald et al., 2013). Easton (2009) argued that protocols help organize dialogue and promote reflection on teaching practices. Thus, protocols can function as a key mechanism for making the process of PCK development—the exchange and refinement of knowledge within the PLCs—both visible and analyzable.

However, despite the widespread advocacy for PLCs, a significant gap remains in the empirical literature. Many studies on PLCs rely on self-reports or general discourse analysis, often failing to provide detailed documentation of the underlying processes of teacher change (Dogan et al., 2016). This lack of process-oriented evidence highlights the need for research that implements structured PLCs and employs a robust theoretical framework, such as the RCM's lens on knowledge exchange, to systematically capture and analyze the mechanisms of PCK development as they unfold.

Pedagogical Demands of MBI

The MBI is a teaching strategy that actively engages students in constructing scientific knowledge, allowing them to experience the nature of scientific inquiry firsthand. Models serve as diverse forms of representation to explain natural phenomena and fulfil four key purposes: visualizing, explaining, communicating, and predicting (Gobert, 2000; Harrison & Treagust, 2000; Somerville & Hassol, 2011; van Driel & Verloop, 1999). MBI does not conclude at the model-generation stage; rather, it is a cyclical process encompassing ongoing model evaluation and modification phases.

A key concept in this context is meta-modeling knowledge, which refers to an individual's understanding of the nature, purpose, and processes involved in modeling. This knowledge is essential because it enables students to actively participate in MBI and apply their knowledge and skills related to models across various contexts (Abd-El-Khalick et al., 2004; Schwarz et al., 2009). Meta-modeling knowledge is critical in supporting students' learning about the nature of science through modeling and serves as a core element in fostering scientific thinking.

Prior studies have reported that MBI positively influences students' understanding of scientific concepts, inquiry skills, and comprehension of the nature of science (Manz, 2012; Schwarz & White, 2005). In primary education, MBI has also been demonstrated to enhance students' abilities to simplify and interpret natural phenomena while encouraging creativity and logical thinking (Lehrer & Schauble, 2010; Park et al., 2020).

Despite these benefits, the implementation of MBI in classrooms remains limited. One key reason, as cited in the literature, is that teachers often lack a sufficient understanding of how to conduct MBI effectively (Crawford & Cullin, 2004; Louca & Zacharia, 2012; Oh & Oh, 2011; van Driel & Verloop, 2002; Vo et al., 2019).

To conduct MBI effectively, teachers must be capable of designing developmentally appropriate activities, sequencing modeling activities to align with the logical progression of a lesson, and providing timely and constructive feedback throughout teaching. Consequently, successful MBI requires PCK, which integrates students' knowledge of teaching strategies, assessment, and understanding (Nelson & Davis, 2012). Developing this high-level, practice-based PCK is a significant challenge for teachers to overcome in isolation, underscoring the critical role of collaborative professional development environments like PLCs.

Tracing PCK Development through the IMTPG Analysis Framework

This study employs the Interconnected Model of Teacher Professional Growth (IMTPG) proposed by Clarke and Hollingsworth (2002) to analyze the multifaceted nature of teacher growth. To capture the complex reality of this growth, the IMTPG provides a detailed analytical map articulating teacher change across four key domains and two mediating processes.

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The four domains constitute a teacher's world: the personal domain (teachers' knowledge, orientation, attitudes); the external domain (professional development, peer collaboration); the practice domain (actual teaching practices); and the consequence domain (student responses, learning outcomes). These domains are not isolated but are organically connected, and their interactions are mediated by two key processes: enactment, where knowledge is transformed into action, and reflection, where practice is examined to deepen knowledge. The model further captures this evolution by distinguishing between change sequences—short-term, bounded pathways of change—and growth networks, representing expertise's sustained and cumulative expansion as multiple change sequences become interconnected.

The IMTPG has proven to be a versatile framework for examining science teachers' PCK development across various contexts, from tracking the pathways of pre-service teachers (e.g., Jong et al., 2005) to analyzing professional development for in-service teachers in complex areas like MBI (Justi & van Driel, 2006). However, while these studies confirm the IMTPG's utility in tracking that change occurs, they offer less insight into how the specific, moment-to-moment processes of knowledge exchange fuel this growth.

This is precisely where the RCM becomes critical, providing a powerful lens for analyzing these knowledge exchanges. While the RCM offers the theoretical framework, PLCs provide the practical context for teacher growth, and MBI represents the key area of expertise they aim to develop. However, despite the individual importance of these elements, a significant gap exists in understanding how they work in concert—specifically, how primary school teachers' PCK for MBI develops within a PLC through the knowledge exchange described by the RCM.

Against this backdrop, this study examines how primary school teachers' PCK develops through participation in a PLC focused on MBI. To achieve this, the IMTPG, along with the RCM's framework of knowledge exchange across PCK domains, is utilized to analyze the processes underlying the PCK development among participating primary school teachers.

Based on these frameworks, this study addresses the following research questions:

1. How do primary school teachers' PCK develop through their participation in a PLC centered on MBI?
2. How do teachers' knowledge exchange and developmental pathways emerge when analyzed through the combined IMTPG–RCM framework?

Research Methodology

Design

This study explored how primary school teachers' PCK developed through their participation in a PLC designed to enhance their MBI expertise. To achieve this, a PLC protocol was developed specifically to support primary school teachers in reflecting on their teaching and systematically acquiring standardized knowledge related to MBI. Participants were recruited, and five PLC sessions were conducted based on this protocol.

Following the fourth session, participating teachers implemented modeling-based lessons in their respective classroom contexts. After completing these lessons, the fifth PLC session was held, during which the participants collectively reflected on their experiences implementing the MBI. In the final session, they engaged in collaborative discussions about the characteristics of effective MBI and the teacher and student competencies required for its successful implementation.

To capture teachers' professional growth in detail, this study employed an analytical framework combining knowledge exchange processes among the three PCK realms (cPCK, pPCK, and ePCK) proposed in the RCM, with the IMTPG. The development of PCK was examined through a multilayered analysis of various data collected before, during, and after PLC participation, including PLC discourse, in-depth interviews, Content Representation (CoRe) documents, and artifacts of teaching practice. This qualitative case study was conducted with three primary school teachers from the Seoul metropolitan area over 12 weeks between July and October 2023.

Participants

Participants were selected from a pool of primary school teachers with limited prior experience with MBI. However, they demonstrated high interest, motivation, and commitment to developing their science teaching expertise. This decision was informed by research indicating that teachers' affective factors, such as personal orientations and motivation, play a critical role in shaping their uptake of new teaching strategies (Hand et al.,

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2016), and that more discernible patterns of PCK development are evident when comparing pre- and post-PLC participation and teaching enactment.

Teaching experience is also a key factor influencing PCK development (Lee, 2006). Therefore, teachers with varying years of experience were selected to examine how PCK development varies across different stages of the teaching career. Recruitment was conducted over two weeks through a posted announcement in an online community for primary school teachers. Three primary school teachers from schools in the Seoul metropolitan area were selected using purposive sampling. Participants' characteristics are presented in Table 1.

Table 1
Background Information of Participants

Name (pseudonym)	Anna	Brian	Carol
Gender	F	M	F
Years of Teaching Experience	1	7	12
Education Level	B.S.	M.S.	M.S.
Grade Level Taught	5	5	5,6
Science Teaching Role	Homeroom teacher teaching science	Homeroom teacher teaching science	Subject-specialist teaching science

Note. In the Korean primary school system, homeroom teachers are typically responsible for teaching most subjects, including science. In some cases, science is taught by a subject-specialist teacher.

Data Collection

This study collected data from four sources: PLC discourse, in-depth interviews, CoRe, and artifacts of teaching practice to comprehensively examine the development of teachers' PCK before, during, and after the PLC and the implementation of MBI.

i) PLC Discourse

Five PLC sessions were conducted following this protocol, and the activities included in each session are summarized in Table 2. This protocol was adapted from the framework proposed by Lee et al. (2022), which was initially designed to support inquiry-based teaching and modified to align with the objectives of developing MBI expertise.

All participant discourses during the five PLC sessions were recorded and transcribed. These sessions involved exploring the meaning of MBI, sharing modeling-based teaching experiences, learning standardized knowledge related to MBI (cPCK), lesson planning, and post-teaching reflection. Through analysis of these sessions, the analysis focused on how knowledge shared during PLCs influenced individual teachers' professional knowledge through teacher-to-teacher dialogue.

Table 2
Configuration of PLC Sessions for Enhancing Teaching Expertise in MBI

Category	Title	Content	Duration
PLC Session #1	Expressing thoughts on MBI	What does MBI mean to me? Why is modeling essential in school science classes? What constitutes a good MBI?	70 min
PLC Session #2	Sharing experiences of MBI and student outcomes	Sharing my experiences in science modeling or MBI What defines a successful MBI? Presenting student outcomes from lesson cases What should we look for in student outcomes from MBI?	90 min
PLC Session #3	Building competence in teaching MBI	Understanding MBI Capturing student learning in activity cases Exploring strategies for guiding MBI	70 min

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Category	Title	Content	Duration
PLC Session #4	Planning lessons	Based on the activities conducted in PLC sessions #1-3, develop a lesson plan that demonstrates competence in guiding MBI	120 min
PLC Session #5	Reflecting on MBI	Sharing examples of successful and less successful MBI What defines a good MBI? What skills are required of students participating in MBI? What competencies should teachers possess for successful MBI?	150 min

ii) In-depth Interviews

To understand how knowledge exchange in the PLC influenced the participants' PCK development, each teacher participated in two in-depth interviews. The first interview, conducted one month after the fourth PLC session, explored the impact of PLC participation on the pPCK and ePCK. The second interview involved a member-checking process, where participants reviewed the transcript from the first interview. Based on this review, follow-up questions were developed to clarify ambiguous responses and elicit more specific insights. This study examined how teachers transformed cPCK acquired during the PLC into their individual teaching knowledge (pPCK). All interviews were video-recorded with the participants' consent, and they were asked to verify the accuracy of the initial transcriptions.

iii) CoRe

CoRe is a tool that supports teachers in organizing their teaching strategies for specific science topics, thereby promoting more effective student learning (Loughran et al., 2004, 2006). For each designated topic, teachers identified the key concepts—referred to as "big ideas"—and answered eight associated questions (see Table 3). These questions prompted teachers to reflect on what students should learn, why they should learn, and which teaching considerations are necessary for teaching each big idea effectively. In response to these questions, teachers drew upon their knowledge of science teaching orientations, curriculum content, students' understanding, instructional strategies and representations, and assessment practices (Barendsen & Henze, 2019; Bertram & Loughran, 2012).

The CoRe process helped teachers externalize their tacit pPCK (Alonzo et al., 2019) and visualize how the various components of their PCK are interconnected in relation to specific science topics (Hume, 2015; Hume & Berry, 2013; Kind, 2009; Mazibe et al., 2020; Nilsson & Loughan, 2012; Rollnick et al., 2008). In this study, teachers completed the CoRe three times: once before PLC participation, once before lesson implementation, and once after lesson completion. These three CoRe documents were used to compare temporal changes in participants' pPCK.

iv) Artifacts of Teaching Practice

As ePCK emerges throughout the whole teaching cycle—including planning, teaching, and reflection—it is essential to collect data at various stages to document how it develops (Park, 2019). Moreover, ePCK is considered the most implicit of the three PCK realms in RCM and must be observed within actual teaching contexts (Alonzo et al., 2019). Therefore, multiple data sources were collected before, during, and after the implementation of lessons to capture the emergence and development of ePCK.

The first data source consisted of lesson plans. Participants created detailed teaching plans based on the collaboratively designed PLC lesson plan for the "Living Things and Environment" unit (see Table 4), incorporating specific classroom activities, teacher utterances, and assessment strategies for each session. The second source involved video recordings of classroom teaching. A total of 11 lessons were recorded and transcribed. Teachers' verbal interactions and teaching behaviors were analyzed to examine how their ePCK manifested during teaching. The third data source comprised video-stimulated recall interviews and PaP-eR. After teaching, teachers participated in interviews using selected video clips to revisit key teaching episodes and explore their pedagogical reasoning. Pedagogical and professional experience repertoires (PaP-eRs) are short narrative vignettes that describe specific moments of teaching decision-making (Loughran et al., 2001). Each PaP-eR includes a teaching context, a student's response, and the teacher's rationale for their actions (Alonzo et al., 2019). By analyzing these three sources collectively, this study aimed to identify how changes in ePCK during teaching contribute to the subsequent development of pPCK.

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Table 3
CoRe (Content Representation) Template (Loughran et al., 2004; 2006)

Prompts	Big Idea A	Big Idea B	...
1. What do you intend the learners to learn about this idea?			
2. Why is it important for learners to know this?			
3. What else do you know about this idea (that you do not intend learners to know yet)?			
4. What are the difficulties/limitations connected with teaching this idea?			
5. What is your knowledge about learners' thinking that influences your teaching of these ideas?			
6. Are there other factors that influence your teaching of these ideas?			
7. What are your teaching procedures (and particular reasons for using these to engage with this idea)?			
8. Specific ways of ascertaining the learner's understanding or confusion around this idea (include a likely range of responses).			

Note. Adapted from Loughran et al. (2004, 2006).

Data Analysis

Raw data were analyzed, including PLC discourse, in-depth interviews, CoRe, and artifacts of teaching practice, to trace the development of participating teachers' PCK, focusing on four core components of PCK identified by Magnusson et al. (1999): Knowledge of Science Curriculum (KSC), Knowledge of Students' Understanding in Science (KSU), Knowledge of Instructional Strategies and Representations (KISR), and Knowledge of Assessment of Science Learning (KAS).

All data were first carefully read, and utterances or text segments deemed relevant to a specific PCK component were coded, using consistently meaningful statements as the unit of analysis. For instance, if a teacher described student misconceptions or anticipated learning difficulties in the CoRe, the statement was coded as "KSU." Similarly, if a teacher mentioned improving assessment methods during an interview, the statement was coded as "KAS." After coding the data independently, any discrepancies were resolved through discussion and consensus to ensure coding reliability.

Next, each coded segment was further categorized according to the three PCK realms from the RCM (cPCK, pPCK, and ePCK) and the four domains from the IMTPG: external domain (ED), personal domain (PD), domain of practice (DP), and domain of consequence (DC). The meanings of these domains were redefined to align them with the context of this study, and then a combined coding system was implemented accordingly.

For instance, standardized knowledge of MBI shared within the PLC was coded as cPCK and ED. Utterances or texts reflecting teacher orientation changes or existing knowledge were coded as pPCK or PD, respectively. Lesson planning, classroom teaching, and reflection were coded as ePCK and DP, respectively. Student responses and learning outcomes observed during teaching were coded as ePCK and DC, respectively.

Each unit was assigned a compound code representing the PCK component and its corresponding RCM and IMTPG domains (e.g., KSU, pPCK/PD or KISR, ePCK/DP). A cross-checking process was conducted to ensure consistency and validity in the coding scheme. Subsequently, to trace the knowledge exchange among the RCM realms (cPCK, pPCK, and ePCK), the data were analyzed to determine how specific types of knowledge transitioned or interacted across the realms. For instance, when a teaching strategy introduced in the PLC (cPCK) was internalized by a teacher (pPCK) and later applied in practice (ePCK), this sequence was interpreted as a transition: cPCK → pPCK → ePCK. In parallel, the IMTPG framework was used to analyze how knowledge and orientation evolved through the mediating processes of enactment and reflection across the four domains. According to Clarke and Hollingsworth (2002), teacher change can occur in two forms: a change sequence, which refers to a short, bounded progression in which a change in one domain leads to a change in another; and a growth network, which refers to a sustained, cumulative development formed by the connection of multiple change sequences.

Following the criteria proposed by Justi and van Driel (2006), instances involving only one or two simple linkages were categorized as change sequences. In contrast, those with three or more repeated interactions across domains, indicating expanded professional knowledge, were classified as growth networks. To apply this classification, the coded data were mapped chronologically and analyzed to identify how changes in specific PCK components moved

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across domains. For instance, if a teacher identified a student's learning difficulty (DC), reflected on its cause (PD), revised the lesson plan accordingly, implemented it (DP), and subsequently reflected again on the effectiveness of the new strategy (PD), this process would be considered a cyclical structure forming a growth network.

Finally, to visualize teacher growth pathways, transitions between the IMTPG domains were represented diagrammatically. A circle or square represented each of the four IMTPG domains, and arrows indicated domain-to-domain changes over time. The numbers on the arrows denote the chronological order of the changes. These visual maps facilitated comparisons of the complexity and density in each teacher's growth trajectory, highlighting whether they exhibited rich growth networks or limited change sequences. The growth diagrams for all three teachers were displayed side by side to identify shared and unique patterns.

In addition, these patterns were analyzed in connection with personal factors such as teaching experience, teaching orientation, and classroom context to gain deeper insights into individual PCK development characteristics. Throughout the analysis, peer cross-validation and member checking with participants were conducted to ensure the credibility and validity of our coding and interpretation.

Table 4

Organization of the Modeling-Based Instruction for the Unit "Living Things and Environment"

Session	Key Questions	Main Activity Content
1	What is an ecosystem?	• Learn what a model is, see examples, understand the modeling process, and know the purpose of modeling activities • Learn about living things and non-living things • Learn about different types of ecosystems
2-3	How do living things influence each other?	• Sort living things into producers, decomposers, and consumers based on how they get nutrients • In groups, generate, evaluate, and modify a food web model
4-5	How do non-living factors affect living things?	• Design a model and an experiment to show how non-living parts of the environment affect living things (make a hypothesis, plan the experiment, and predict the results) • Carry out the experiment using your model • Use a model to show the relationship between living things and non-living things
6-7	How do living things adapt to their environment?	• Explore examples of how living things adapt to their surroundings • Generate a model to show how the environment affects living things, especially those that live in extreme conditions • In groups, evaluate and modify your model
8-9	What is ecological balance?	• Look at examples of ecological balance • In groups, generate a model that shows how an ecosystem can return to balance. • In groups, evaluate and modify your model
10-11	Unit Review	• Discuss ways we can help protect our ecosystems • Review the main ideas learned in this unit • Share your thoughts about the modeling activities

Research Results

Changes in Primary school teachers' PCK Through Participation in a PLC Focused on MBI

i) Changes in Knowledge of Science Curriculum (KSC)

KSC refers to teachers' understanding of big ideas and materials for a unit and their knowledge of horizontal and vertical curricula (Magnusson et al., 1999). The analysis revealed that while Anna and Carol showed no significant changes in KSC when comparing their CoRe documents before and after the PLC, Brian demonstrated a qualitative improvement in his KSC following the implementation of the MBI.

Anna and Carol demonstrated a strong KSC in their initial CoRe submissions before PLC participation. They showed a deep understanding of the unit's big ideas and exhibited a strong knowledge of horizontal and vertical curriculum alignment, using this knowledge to plan lessons. For instance, Anna wrote that "students needed to understand food chains because they serve as foundational knowledge for understanding the flow of energy

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and cycling of matter in ecosystems," indicating an awareness of concepts introduced in higher grades. Similarly, Carol articulated a solid grasp of key concepts, including "the distinction between biotic and abiotic components, food chains, and human impacts on ecosystems." These examples suggest that both teachers already possessed well-developed KSC, which likely contributed to the relatively limited growth observed in this area following PLC participation.

In contrast, Brian's initial CoRe displayed limited and occasionally inaccurate content representations of the unit. In the first CoRe, he wrote, "It is difficult to explain prokaryotes and eukaryotes," referring to content inappropriate for the grade level and misaligned with curricular objectives. His second CoRe showed minimal progression, stating again, "It is difficult to clearly define 'living things,' distinguish between prokaryotes and eukaryotes, and differentiate between living and non-living things," highlighting a continued misalignment with curricular standards.

However, in the third CoRe, completed after implementing the MBI, Brian's descriptions of unit content aligned much more closely with the curriculum. He also noted, "Food webs and food chains are models that help students understand the principles of ecological balance and energy flow in ecosystems." This statement reflected an awareness of both the cognitive and pedagogical value of models. This awareness aligns with the concept of meta-modeling knowledge, as defined by Schwarz et al. (2009). By integrating KSC with meta-modeling knowledge, Brian demonstrated a more advanced and curriculum-aligned understanding of science content.

ii) Changes in Knowledge of Students' Understanding in Science (KSU)

KSU refers to teachers' awareness of students' prior knowledge and misconceptions and their understanding of students' abilities and attitudes that influence learning (Magnusson et al., 1999). Anna had already shown attentiveness to student misconceptions before participating in the PLC. However, after implementing the MBI, she advanced beyond simply identifying misconceptions to articulating targeted teaching strategies to mitigate them. For instance, in the fifth PLC session, she emphasized avoiding teacher questions or classroom activities that might reinforce misconceptions. She also proposed the use of scaffolding strategies to support students' understanding. This indicates that Anna's KSU deepened following the lesson, enabling her to anticipate misconceptions and proactively plan responsive strategies to address them.

However, Brian initially focused more on difficulties from the teacher's perspective rather than considering students' perspectives. In his pre-instruction CoRe, he wrote that while teaching food webs and food chains, "It is easy to help students understand the model, but it is difficult to explain the exceptions." This reflects a teacher-centered orientation, where challenges regarding teaching delivery rather than student cognition are framed. However, after the MBI implementation, Brian's perspective shifted noticeably. In the fifth session, he highlighted the importance of helping students recognize the differences between their models and real-world phenomena to prevent misconceptions. He further noted, "Evaluating and modifying models is still difficult for students, so they should first go through the process of generating and modifying models individually." These comments reflect an increased awareness of students' cognitive difficulties during modeling and signal a transition from a teacher-centered orientation to a student-centered orientation at KSU.

The most experienced teacher, Carol, had already exhibited high KSU levels before the PLC. In her first CoRe, she designed lessons based on students' prior knowledge and potential misconceptions. In the fifth PLC session, following the MBI implementation, she reflected more deeply on the affective factors that influenced students' engagement in modeling. She stated, "Students need some background in science knowledge and inquiry skills, but more than just being receptive, they also need a critical attitude, especially in the model evaluation stage. They need courage to critique and challenge other groups' models." This remark illustrates Carol's recognition that affective traits, such as critical thinking and confidence, play a crucial role in student participation and learning in MBI. Her perspective evolved from addressing misconceptions to considering how students' skills and attitudes influenced their modeling engagement, reflecting a more complex and integrated understanding of KSU.

In summary, all three teachers exhibited positive developments in their KSU. Anna progressed by articulating specific strategies to address misconceptions. Brian shifted from a teacher-centered view to focusing more on students' learning difficulties and conceptual challenges. Carol, who already had a firm grasp of the students' understanding, deepened her knowledge by integrating cognitive and affective factors into her teaching planning.

iii) Changes in Knowledge of Instructional Strategies and Representations (KISR)

KISR refers to teachers' knowledge of instructional strategies to help students achieve their learning objectives. Before participating in the PLC, all three teachers primarily planned lessons emphasizing research and presentation activities. They understood modeling activities as representational tasks for depicting natural phenomena.

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However, through the PLC, they engaged with meta-modelling knowledge. They shared various examples of MBI, leading all three teachers to plan and implement teaching strategies aligned with the model generation–evaluation–modification (GEM) cycle. This cyclical framework was first introduced by Clement (1989).

Specifically, Anna, in her first CoRe prior to the PLC, designed a lesson on ecosystem equilibrium where "students use smart devices to research various examples of ecosystem balance and present their findings." However, her second CoRe described a more explicit modeling strategy: "Student groups create models to explain ecosystem equilibrium, compare and evaluate them with other groups, and then modify them." Although Anna planned all the modeling stages, she had to simplify the process during teaching owing to time constraints. In the fifth PLC session, she reflected on this and proposed incorporating digital tools to streamline the MBI process:

> "If I had prepared some basic hints in advance, like simple food chain relationships, or allowed students to use laptops or tablets for searching, the model generation and modification process would have been more efficient."

Brian also had a limited understanding of the MBI before the PLC. However, through the PLC, he became familiar with MBI strategies and attempted to integrate them into his teaching. He planned to include the entire GEM cycle in his lessons. In practice, however, students spent significant time generating models, leaving little time for evaluation and modification. Consequently, partway through the unit, he revised his strategy for subsequent lessons, opting for a teacher-guided model evaluation. Afterward, he reflected on the following:

> "When students created models, they focused more on making them visually appealing than on expressing scientific concepts, which took much time. Eventually, not all the models were evaluated, and there was no time for modification. Next time, I think it would be better to run only specific stages, such as model generation or evaluation, in a single class period to keep it simpler."

Based on this reflection, Brian began considering more streamlined teaching structures that targeted specific stages of MBI rather than attempting to implement the entire cycle in a single session.

Carol originally designed research-based activities in her first CoRe, like the other two teachers. However, after recognizing the teaching value of modeling through the PLC, she incorporated MBI strategies into her lessons. She also encountered time constraints during teaching, but addressed this issue by adding a class period. During teaching, she observed that repeated opportunities for feedback improved the specificity and sophistication of the students' evaluations of each other's models. She reflected:

> "The first feedback was quite general, but the students gave more specific evaluations of each other's models by the second time. I could see that their model evaluation skills improved through multiple rounds of feedback; therefore, I plan to include both the model evaluation and modification stages more deliberately in future lessons."

In the final PLC session, Carol emphasized that effective MBI depends on student-to-student interaction, stating, "A good modeling lesson allows students to learn by seeing various models and engaging with their peers. To enable that, I think teachers must provide specific feedback to promote interaction continuously."

In summary, all three teachers developed a clear understanding of MBI strategies through the PLC and attempted to implement the GEM cycle in their teaching. Anna and Brian adjusted their teaching plans in response to time limitations and student reactions by simplifying the modeling process. In contrast, Carol was able to observe and leverage student growth in model evaluation and apply these insights into her future teaching planning. Although all three teachers exhibited common patterns in refining and adapting their teaching strategies based on post-implementation reflections, variations emerged in the structure and focus of their KISR approaches.

iv) Changes in Knowledge of Assessment of Science Learning (KAS)

KAS refers to teachers' knowledge about the principles and practices of assessing science learning (Magnusson et al., 1999). Before participating in the PLC, all three teachers primarily regarded assessment as a tool for verifying students' conceptual understanding, and accordingly, they planned assessments that were predominantly centered on written tests. However, after participating in MBI as learners and engaging in collaborative discussions on effective student assessment practices, they exhibited meaningful changes in their perspectives on assessment and the methods they applied.

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Changes in Assessment Perspectives

Anna and Carol broadened their perspectives on assessment, moving beyond simply checking learning outcomes to viewing assessment as a tool that enhances learning and provides feedback. Anna's first and second CoRe entries relied solely on the assessment criteria outlined in the national curriculum achievement standards. However, in her third CoRe, she developed new assessment criteria specifically tailored to the context of the MBI. For instance, in a lesson on food webs, she proposed evaluating whether "students can represent a food web as a model" and whether "they can distinguish between food chains and food webs and explain the complexity of food webs." This shift reflects a move toward assessing students' understanding of ecological complexity and system stability, concepts that extend beyond the curriculum's original assessment indicators.

Similarly, during a lesson on the impact of abiotic factors on living organisms, Carol observed the students independently designing and conducting experiments. Rather than focusing solely on the results, she suggested assessing inquiry skills and collaborative interactions, such as "whether students can identify flaws in their experimental design" and "whether they can arrive at a shared conclusion through peer feedback." Consequently, Carol expanded her assessment criteria beyond a narrow focus on official learning standards to include students' ability to design experiments, conduct research, and the effectiveness of peer collaboration in improving inquiry outcomes.

Changes in Assessment Methods

Regarding assessment methods, all three teachers began to recognize the value of using student-created scientific models as assessment tools. Before the PLC, they tended to rely on a single method to evaluate students' understanding of each big idea, with only a few instances using two methods per concept. However, after the PLC, they increasingly acknowledged the importance of employing multiple assessment tools within a single lesson. In their later teaching phases, they began integrating various tools such as peer evaluations and performance-based tasks. By the third CoRe, nearly every big idea was associated with two to three distinct assessment methods.

Notably, all three teachers included "student-created models" as assessment tools for their second and third CoRe entries. The fact that these models were listed not only in their teaching strategy plans but also as evaluation tools suggests that the teachers came to view modeling as both an effective means of teaching and a valid method of assessment.

Pathways and Knowledge Exchanges in the Development of Teachers' PCK

i) Knowledge of Science Curriculum (KSC)

Anna and Carol demonstrated a strong, well-developed KSC from the outset, as evident in their first CoRe, written prior to participating in a PLC focused on MBI. This depth of understanding was maintained throughout the Third CoRe. The strength of their KSC before teaching implementation can largely be attributed to their professional backgrounds. Carol, the most experienced among the participants, aligns with prior research suggesting that more teaching experience correlates with greater curriculum knowledge (Mulholland & Wallace, 2005). Although relatively early in her career, Anna had recently prepared for the national teacher certification exam, during which she studied the curriculum intensively, thereby gaining a high level of understanding of the unit.

Both teachers implemented their teaching based on their already high pPCK (PD → DP) and later restructured that knowledge through reflection after teaching (DP → PD). From the perspective of the IMTPG, this represents a change sequence and a relatively bounded path of development. In RCM terms, this reflects the knowledge exchange between ePCK and pPCK, representing refinement rather than the transformation of existing teacher knowledge.

In contrast, Brian initially exhibited limited KSC prior to teaching, as evidenced by his first and second CoRe, in which he either omitted or inaccurately described the big ideas of the unit. However, while planning and implementing his lessons, he reviewed and reorganized the unit's learning elements and sequence to align them with the flow of MBI (PD → DP). He paid particular attention to the modeling activities that students engaged in during each lesson, and sought to logically link learning objectives with modeling activities. In his first interview, Brian reflected the following:

> "I ended up reorganizing a lot of the content. I changed the lesson sequence and merged the two lessons to run them back-to-back in a single day. During planning, I considered the overarching structure and flow of the unit. If I had planned the lesson independently, I would probably not have gone this far. I would have followed the textbook without any major changes. However, this restructuring helped me think about how to link curriculum elements and modeling activities more organically."

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In the fifth PLC session, Brian further reflected:

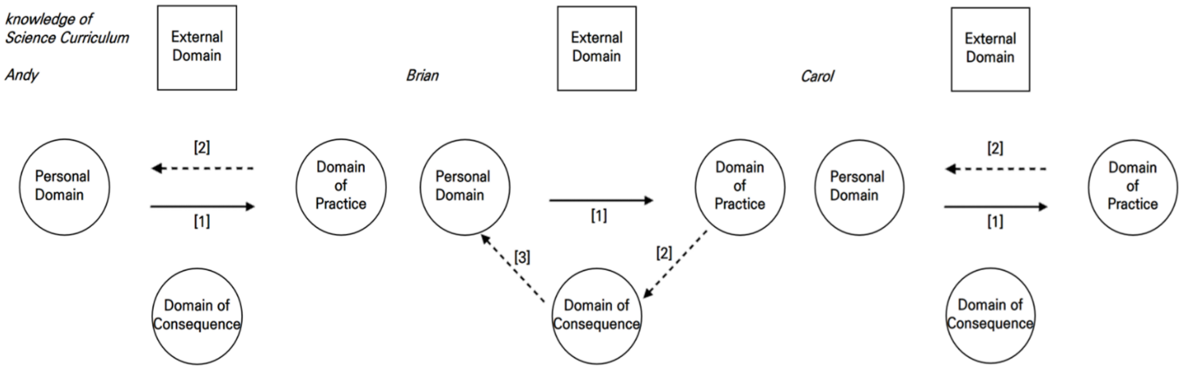
> "Because we planned to explore abiotic factors and their effects on living things in the next session, I excluded them from this one to reduce cognitive load. In this way, the students could better focus on modeling food chains and webs. I was satisfied with this decision."

This reflection illustrates that Brian identified positive student responses (DP → DC) and restructured his KSC accordingly by adjusting the scope and sequence of content in future lessons (DC → PD). According to the IMTPG analysis, Brian established a "growth network" to expand progressive teacher knowledge. This was achieved through an iterative cycle of PD → DP → DC, which interconnected three or more domains. Thus, Brian's teaching process reflects a developmental progression, wherein he restructured his pPCK by exchanging knowledge between his ePCK and pPCK during his teaching and incorporated these changes into his next lesson.

In summary, the developmental pathways in KSC differed based on teachers' prior knowledge and teaching experiences. Anna and Carol enacted their teaching based on strong existing pPCK, which they later refined through reflection; however, the overall scope of development was limited. On the other hand, Brian began with a limited understanding of the curriculum but demonstrated a clear growth path. He developed ePCK through lessons and then expanded his pPCK through knowledge exchange. This indicates that each teacher's pre-existing knowledge and classroom experience are crucial factors that significantly influence the outcomes of PLC activities, particularly regarding the development of curricular knowledge.

Figure 1

Development Pathways of Teachers' Knowledge of Science Curriculum (KSC) Based on the IMTPG Model



ii) Knowledge of Students' Understanding in Science (KSU)

As identified in Research Result 1, all three teachers demonstrated qualitative growth in their KSU following the PLC. Anna moved beyond recognizing students' misconceptions to articulating specific teaching strategies to prevent them after the PLC. Brian shifted his previous perspective of focusing on teachers' difficulties and turned his focus toward the difficulties and misconceptions students face during learning. Carol, who already possessed a high level of KSU, including students' prior knowledge and misconceptions, expanded her perspective to include students' abilities and attitudes, such as inquiry skills and critical attitudes, after the PLC. Although the three teachers grew up in different aspects of student understanding, such as misconception-focused teaching strategies, a student-centered perspective, and understanding learner characteristics, they all restructured their KSU by reflecting on their own teaching practices and student responses.

Anna experienced MBI from a student's perspective during the PLC and became concerned about students forming misconceptions during the model generation process (ED–PD). She then applied various prevention strategies to her lessons (PD → DP). However, Anna observed student responses that differed from her expectations during implementation (DP → DC), and she subsequently shared a more refined misconception prevention strategy in the CoRe and PLC discussions (DC → PD → ED). Through this process, Anna formed a growth network that iteratively cycles through the four domains of the IMTPG model. From the RCM perspective, through knowledge exchange between cPCK and pPCK (e.g., participating in modeling instruction as a student and sharing student

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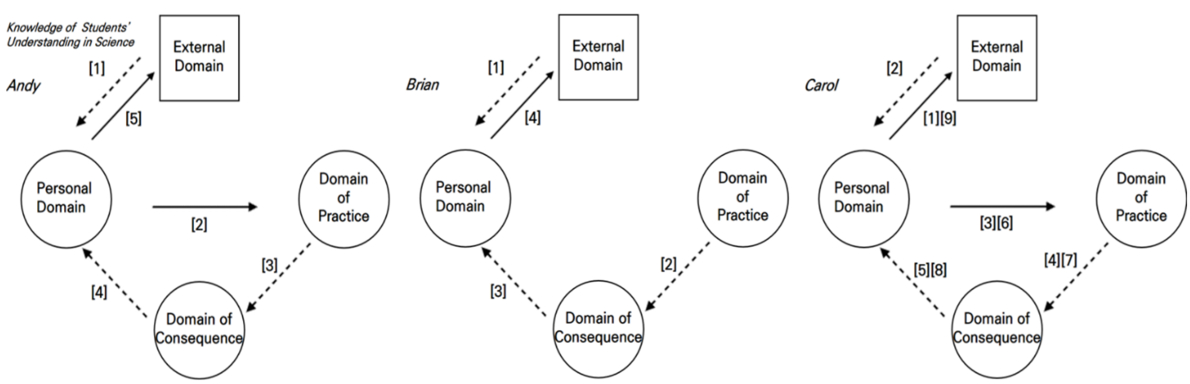
support methods in the PLC) and between ePCK and pPCK (by observing student responses in class), she expanded her pPCK beyond merely recognizing student misconceptions to develop teaching strategies to prevent them.

Brian initially focused on the challenges teachers face when implementing MBI, but through discussions with his peers, he became interested in the difficulties students experienced in modeling-based learning (ED–PD). In his class, he observed the challenges faced by students lacking scientific knowledge during the model generation process, as well as the responses of students who did not clearly recognize the difference between the model and reality (DP → DC). Subsequently, in the third CoRe and the fifth PLC session, he proposed concrete strategies such as "generating a collective model after individual model generation" and "clear teacher guidance on the difference between a model and reality" (DC → PD → ED). This demonstrates his shift from a teacher-centered to a student-centered perspective. While the domain connections in his IMTPG path are relatively limited, they represent a qualitative change in his focus. From an RCM perspective, the collective knowledge (cPCK) of student support methods discussed in the PLC was converted into Brian's pPCK. The knowledge formed through lesson implementation and reflection on student responses (ePCK) was then integrated back into pPCK, and this refined pPCK was shared again in the fifth PLC session, feeding back into cPCK. Knowledge exchange between ePCK and pPCK was prominent in Brian's development, showing that a teacher's knowledge of student understanding can be progressively restructured through teaching experience.

Carol already possessed a high level of pPCK before the PLC and actively shared specific ideas for student support methods, thereby converting it to cPCK (PD → ED). She then refined her student support methods based on ideas from discussions with other teachers and applied them in her lessons (ED → PD → DP). By closely observing the effects, she repeated a growth cycle of DP → DC → PD, expanding her knowledge of student understanding through the exchange between ePCK and pPCK. Carol recognized that not only students' misconceptions but also learners' affective characteristics and inquiry skills influenced MBI. This illustrates that Carol began considering learner factors affecting learning comprehensively. Furthermore, Carol fed her pPCK back into cPCK by sharing her experiences in the fifth PLC session. This can be seen as a process in which KSU develops more comprehensive and contextualized knowledge through exchange among the three PCK domains. In summary, Anna and Carol formed a growth network through knowledge sharing in the PLC and implementing MBI. At the same time, Brian, despite limited connections, showed a growth network in which his pPCK expanded as he achieved a shift in focus away from a teacher-centered perspective.

Figure 2

Development Pathways of Teachers' Knowledge of Students' Understanding in Science (KSU) Based on the IMTPG Model



iii) Knowledge of Instructional Strategies and Representations (KISR)

In planning and implementing MBI, all three teachers attempted to move beyond their existing research- and presentation-focused strategies and expand toward MBI, which included model generation, evaluation, and modification.

Specifically, Anna and Brian reflected on their previous lessons in the second PLC session (DC → PD) and learned about the nature of MBI and various implementation methods (cPCK). Anna, in particular, expressed her agreement with the benefits of this approach (ED → PD), stating, "If students can express what they have learned as a model, I think it will remain in their memory as an image, which would be great." Before the lesson, they collaboratively planned all the stages of model generation, evaluation, and modification (PD → DP). However, in the

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actual classroom, due to constraints such as limited time and students becoming excessively absorbed in the format of the models, they ended up shortening some stages or adjusting them to be teacher-led (DP → DC → DP).

Furthermore, Anna asked students to represent ecosystem equilibrium through role-playing but discovered the potential for misconceptions to arise, as students came to understand the concept as being based on interactions at the individual organism level (DP → DC). Consequently, in the fifth PLC session, she proposed, "I should think about ways to minimize the creation of misconceptions by using drawings, cartoons, or digital devices instead of role-playing" (DC → PD → ED). This led her to recognize the need for the teacher to select and propose appropriate representational formats to prevent students from forming misconceptions as they explained the concepts. Anna also reflected that she could not sufficiently cover the model modification stage due to a lack of time and described a new strategy, "If we have students generate individual models instead of a collective one and conduct evaluations within their groups, I think we could save time and get better results" (DP → PD).

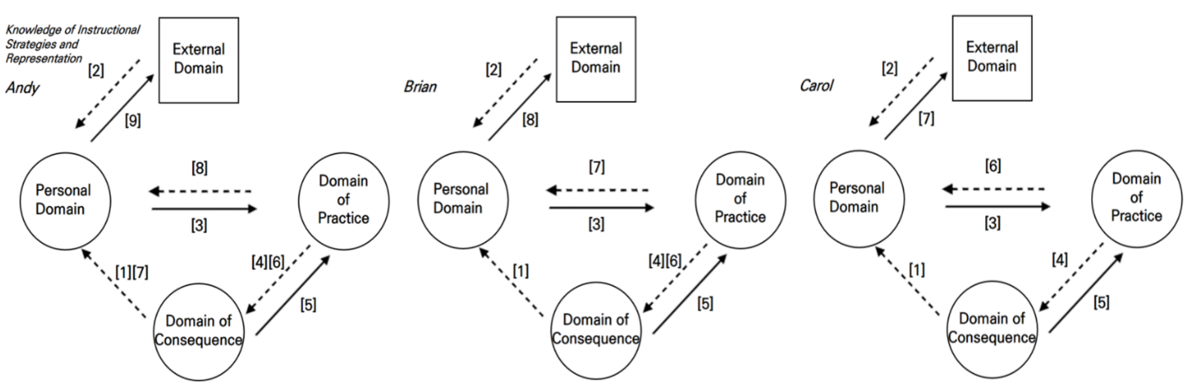
Brian reflected that, because his students spent excessive time generating aesthetically pleasing models, he had no choice but to simplify the model evaluation and modification stages into a teacher-led assessment (DP–PD). During the fifth PLC session, he mentioned, "Instead of trying to conduct all stages in one class session, it might be better to focus on only specific stages, like model generation or evaluation" (PD → ED). Thus, the two teachers converted the ePCK they had formed through lesson reflection into pPCK and restructured their MBI strategies to fit the actual classroom context. These reflections led to ideas for using various representational tools, such as digital devices. Both teachers shared these strategies in the fifth PLC session, contributing to constructing their MBI methods (cPCK).

Carol, after reflecting on her previous lessons in the PLC (DC → PD) and learning about cPCK related to MBI, designed a more sophisticated modeling lesson (ED → PD). As a subject-specialist science teacher, she could flexibly adjust class hours to secure more time, allowing her to faithfully implement the entire modeling process (PD → DP). In her class, students evaluated and modified each other's models twice, which improved the quality of peer feedback and students' understanding of the scientific concepts (DP → DC). Afterward, Carol refined her teaching strategy (DC → DP → PD) based on reflecting that "an intermediate step is needed to help students clearly understand the scientific concepts before model evaluation." In the final PLC, she articulated and shared the strategy she had enacted, emphasizing that "the process of constructing knowledge through student interaction is the essence of MBI" (PD → ED). Thus, Carol integrated the ePCK formed during her teaching into her pPCK to create a more refined teaching strategy and further contributed to the restructuring of cPCK by sharing it in the PLC.

In summary, Anna and Brian demonstrated a growth network in which they adjusted their strategies to address problems encountered during implementation. They contributed to the formation of cPCK by sharing it in the PLC. Carol formed a growth network that highlighted the advantages of the MBI strategy by sharing the positive outcomes of smooth peer feedback and the interactions she experienced in her classroom with other teachers. As such, teachers' KISR changed with various factors, such as their orientation toward modeling, flexibility in lesson management, and student responses. It is evident that through the interaction between pPCK, ePCK, and cPCK, teachers' understanding of and implementation strategies for MBI were continuously refined.

Figure 3

Development pathways of teachers' Knowledge of Instructional Strategies and Representation (KISR) based on the IMTPG model



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iv) Knowledge of Assessment of Science Learning (KAS)

The KAS of all three teachers progressively developed through iterative cycles of external input via the PLC, lesson implementation, and reflection on student responses. Discussions on effective assessment practices during the PLC (cPCK) and teachers' experiences as learners in the MBI acted as external stimuli (ED), which were then internalized into their personal knowledge (pPCK) (ED–PD). Teachers subsequently implemented their assessment strategies in class (PD → DP), and through reflection on student responses (DP → DC → PD), refined their pPCK. This cyclical development pattern reflects a growth network in the IMTPG framework and exemplifies the iterative knowledge exchange among cPCK, pPCK, and ePCK, as described in the RCM.

Anna began by reflecting on her prior lessons (DC → PD) and, through participating in MBI and engaging in discussions with colleagues, reconceptualized her views on assessment (ED → PD). In the PLC, she remarked, "I think I would provide feedback by checking whether the essential concepts are well represented in the models students generate," signaling a shift from assessment-as-verification to assessment-as-learning support. Her expanded pPCK led her to implement multiple assessment methods, including teacher feedback and gallery walk (PD → DP). As students actively engaged in peer assessment (DP → DC), she reflected, "Students enjoyed peer evaluation and participated enthusiastically, but I realized that had I provided clearer guidance on feedback criteria in advance, the evaluations could have been more meaningful." This insight prompted her to incorporate explicit assessment criteria and feedback examples in future lessons (DC → DP), which she documented in her revised CoRe (DP → PD). Anna thus formed a growth network that cycled through reflection on student responses, adjustment of teaching practices, and integration into personal knowledge (DC → PD → DP → PD).

Carol followed a similar trajectory. She began with lesson reflection (DC → PD) and engaged in PLC discussions on effective assessment methods in MBI (ED → PD). Drawing on her revised pPCK, she implemented peer and performance-based assessments in class (PD → DP). In post-lesson interviews, she observed, "When students had enough time to evaluate and modify each other's models, they seemed to learn more from peer feedback than mine" (DP → DC). She further recognized that assessment criteria should prioritize students' ability to identify experimental design flaws and provide quality feedback rather than focusing on the accuracy of representations or model aesthetics. This realization was incorporated into her revised assessment criteria (DC → DP), improving students' attitudes and learning outcomes, and fostering richer student dialogue during lessons (DP → DC). Carol repeatedly exchanged knowledge between ePCK and pPCK, reconceptualizing assessment as an integral part of inquiry and showing a deepening commitment to its continuous practice (DC → PD). Her growth network was characterized by multifaceted refinement cycles across all three PCK domains.

Brian, meanwhile, recognized the need to improve his assessment strategy after reflecting on previous lessons (DC → PD) and learning from peers' shared practices (ED → PD). He incorporated peer evaluation using models in his lesson (PD → DP), but soon realized that student evaluations focused primarily on superficial features like appearance rather than conceptual content (DP → DC). This led him to conclude that more structured guidance was necessary to improve the quality of feedback. He planned to develop a rubric to clarify assessment criteria in future lessons, thus reconstructing his pPCK (DC → PD). While Brian's growth network showed limited domain connections, it marked a meaningful shift in his approach to assessment and revealed the potential for the continued development of KAS.

In summary, Anna and Carol redefined assessment from a tool to confirm learning outcomes to a process that actively supports learning. Through repeated cycles of lesson implementation and reflection, they experimented with strategies such as peer assessment, student-generated models, and explicit criteria. These experiences resulted in dynamic knowledge exchanges across cPCK, pPCK, and ePCK, forming robust growth networks. Though displaying a more modest change, Brian still demonstrated a meaningful transformation in his conceptualization of assessment and commitment to improving assessment practices, suggesting the foundation for future KAS development.

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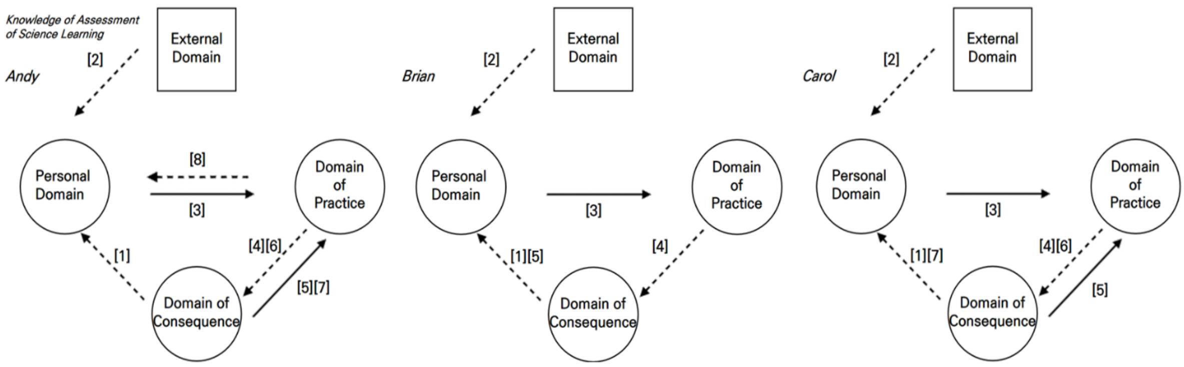
Figure 4

Development pathways of teachers' Knowledge of Assessment in Science Learning (KAS) based on the IMTPG model



Discussion

Pathways and Knowledge Exchanges in the Development of Teachers' PCK

While the PLC effectively fostered the development of participating teachers' PCK, the specific trajectories of their growth varied depending on which PCK components were involved and teachers' individual characteristics. In the KSC, the two teachers who already possessed well-structured curricular knowledge demonstrated a change sequence that primarily involved interactions between the personal domain and the domain of practice, enabling them to refine their pPCK progressively. In contrast, teachers with less-developed curricular knowledge exhibited a cyclical growth network, characterized by ongoing interactions among the personal domain, the domain of practice, and consequence, driven by iterative lesson implementation and reflection. This finding empirically supports Davis's (2004) argument that accumulating practical experience, including implementation and reflection, can drive the development of teachers' curricular knowledge. Furthermore, it suggests that teachers' initial PCK level can significantly influence their developmental processes. Although the three teachers' growth trajectories differed from the RCM perspective, they shared a common feature: all refined their curricular knowledge (pPCK) through knowledge exchange involving reflection on their teaching experiences (ePCK).

At KSU, all three teachers articulated strategies for preventing student misconceptions and supporting students by forming growth networks that operated across four domains: external, personal, practice, and consequence. The RCM perspective indicates that teachers' pPCK evolved through two key exchanges: the internalization of shared knowledge from the PLC (cPCK to pPCK) and the refinement of personal knowledge through lesson reflection (ePCK to pPCK). Reflection on student responses (ePCK) plays a crucial role in KSU's development.

The development of KISR likewise involved all three teachers forming growth networks that operated across the four domains. The teachers reinterpreted the MBI strategies shared in the PLC (cPCK) in line with their individual teaching orientations (pPCK), applied these strategies in their lessons, adjusted them in response to contextual factors, such as time constraints or student responses (ePCK), and further refined them by sharing these adjustments back in the PLC. Notably, how students adjusted their strategies varied according to their personal teaching orientation, aligning with Hashweh's (1996) finding that teaching orientation acts as a primary filter for mediating teaching knowledge and practice.

In the KAS, all three teachers also formed a growth network that continuously engaged with the four domains. Through collaborative discussions and their experiences as learners in the MBI, the teachers reconceptualized assessment to support learning rather than merely verify outcomes. Accordingly, they applied diverse assessment tools, including models, in their lessons and adjusted their assessment methods—or sought new ones—by reflecting on students' responses during implementation. This development was facilitated by internalizing assessment-related cPCK into pPCK and cross-domain knowledge exchange through lesson implementation and reflection (ePCK). This process aligns with Adadan and Oner's (2014) argument that collaborative peer reflection and authentic assessment experiences expand teachers' assessment knowledge and orientation.

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Synthesizing these results, teacher PCK development can be viewed as a complex, context-sensitive process. A key finding was that, except for KSC, all teachers formed complex growth networks that engaged all four domains, aligning with Wongsopawiro et al.'s (2017) assertion that such networks are more effective for PCK development. In this context, the PLC functioned as a forum where teachers, as agents of change, could actively reflect on their practice and outcomes. This process aligns with teachers' perspectives as "adaptive experts" who respond flexibly to new teaching methods and contexts while continuously improving their expertise through reflective thinking (Darling-Hammond & Bransford, 2007). The teachers in this study were actively constructing their PCK as they reflected on student responses, adjusted their strategies, and shared their experiences with their colleagues. This transformation illustrates that the PLC supported teachers in recognizing PCK not as fixed knowledge but as practical, dynamic expertise that is continuously refined through the cyclical structure of knowledge exchange.

Furthermore, this study demonstrates the synergy of integrating the IMTPG and RCM frameworks. The two analytical frameworks offer more than a complementary relationship; they analyze different dimensions, thereby enabling a holistic interpretation of the PCK development process. The IMTPG provides a framework for visualizing the structure and pathways of teacher change, capturing the interactions among its four domains as well as the characteristics of growth over time. Simultaneously, the RCM elucidates the underlying mechanisms of knowledge exchange that drive these structural transformations. It helps explain, in depth, why and how these growth paths were formed through the microprocesses of knowledge exchange among cPCK, pPCK, and ePCK. Consequently, as illustrated in this study, the integrated approach using these two frameworks provides a robust analytical model for future research to explore the multidimensional characteristics and dynamics of teacher professional development—insights that are difficult to obtain through a single perspective alone.

Limitations of the Study

This study has several limitations that should be considered when interpreting the findings. First, as a qualitative case study involving only three primary school teachers, the findings convincingly describe the developmental processes for these specific individuals. However, they cannot claim universality or generalizability to a broader population. Second, the study design cannot fully isolate the specific impact of the PLC participation from other potentially influential variables. Factors such as the act of teaching the MBI unit itself, the teachers' individual reflections, personal characteristics, and the specific instructional contexts were not controlled for, making it difficult to attribute observed changes solely to the PLC intervention. Third, the findings are inherently tied to the specific context: an MBI-focused PLC for primary science teachers in South Korea. PCK development might manifest differently in PLCs focused on other subject areas, different educational levels, or those structured differently. Accordingly, the findings should be interpreted as an illustration of PCK development under these conditions, rather than a universal model. Future research is encouraged to explore teachers' professional development pathways and mechanisms across diverse educational contexts.

Conclusions and Implications

The research findings indicate that, following their involvement in the PLC, all participating teachers demonstrated positive changes across the four components of PCK: KSC, KSU, KISR, and KAS. Although the patterns of change varied among the teachers, a commonality was their reconstruction of PCK through reflective practices on lesson implementation and student responses.

Regarding KSC, teachers with a high level of curricular knowledge exhibited minimal changes. Conversely, one teacher who initially lacked sufficient curricular knowledge included learning objectives in his pre-PLC CoRe that were misaligned with the curriculum's achievement standards. However, after implementing and reflecting on his MBI lessons, he articulated learning objectives more explicitly grounded in the curriculum. Specifically, by recognizing the educational benefits of using models in science classes and reflecting on this in his CoRe, he developed a more advanced form of PCK that merged curricular knowledge with metamodeling knowledge. This finding highlights that the impact of PLC participation differs depending on teachers' initial levels of PCK.

In KSU, KISR, and KAS, all teachers demonstrated changes by adjusting or expanding their existing PCK, primarily through collaborative knowledge sharing with peers and reflective analysis of their MBI lessons. Specifically, teachers developed strategies to prevent student misconceptions (KSU), adjusted instructional strategies informed by the GEM cycle based on implementation outcomes (KISR), and reconceptualized assessment as a tool to facilitate and support learning, incorporating diverse assessment methods, including student-generated models (KAS).

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In summary, this study's findings illustrate that the MBI-focused PLC successfully fostered positive developmental pathways in teachers' PCK, although these pathways varied among individuals. These changes were commonly driven by an iterative cycle of reflective practice, lesson implementation, and knowledge exchange within the community.

This study suggests several future research and practice directions based on these conclusions. Given the study's limited sample and duration, longitudinal research across diverse contexts is needed to analyze long-term PCK development patterns and validate the analytical frameworks used. Such studies could explore how specific events shape individual PCK trajectories and compare the effects of MBI-focused PLCs across different school levels, regions, and teacher experiences.

Furthermore, systematic analysis is required to understand how various factors influence PCK development within PLCs. Future research should examine the interplay between teachers' initial PCK levels, personal orientations, instructional contexts, and school cultures to understand better the mechanisms driving professional growth.

Practically, further research into effective teaching strategies for facilitating MBI is essential, considering classroom constraints like time and varying student skills. Exploring phased approaches to modeling or integrating digital tools could yield concrete strategies for sustainable MBI implementation. Finally, developing customized support strategies within PLCs designs is crucial. Recognizing the diversity in teachers' needs and backgrounds, PLCs should explore tailored approaches, such as mentorship or model lessons, to personalize support and potentially enhance changes in orientation, PCK development, and teaching competency. These directions hold theoretical and practical implications for advancing research on MBI-focused PLCs and the broader field of teacher professional development.

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Declaration of Interest

The authors declare no competing interest.

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Hyunju Kim Seoul Aju Elementary School, South Korea.
E-mail: kailen_kim@naver.com
ORCID: https://orcid.org/0009-0003-9464-9993

Kiyoung Lee *(Corresponding author)* PhD, Professor, Kangwon National University, South Korea
E-mail: leeky@kangwon.ac.kr
ORCID: https://orcid.org/0000-0002-2820-3702